Compensation of thermal optical effects

Technical field

The invention relates to a method for compensating optical thermal effects in accordance with the preamble of Patent Claim 1, an optical unit for this purpose in accordance with the preamble of Patent Claim 4, and an optical arrangement in accordance with the preamble of Patent Claim 10.

Prior art

If optical elements are heated, their optical properties (refractive index, external contour) are generally changed, and this entails variations in the phase front of a beam guided in such elements (thermal lens, thermal birefringence). Thermal optical effects are chiefly extremely disruptive in the case of optical high-performance oscillators, since they worsen the beam quality of the high-performance laser beam to be generated (beam deformation, stress birefringence, beam deflections etc.). The thermal lensing effect and the optical aberrations are caused by anisotropic temperature distribution in the optical medium.

An example for the elimination of thermal optical effects, in particular, continuously operating high-performance CO_2 laser resonators is given in the publication by A.V. Kudryashov entitled "Intracavity Laser Beam Control", SPIE Conf. on Laser Resonator II, San Jose, Calif., pages 32-40; 1999. The compensation is undertaken here actively by means of what is called adaptive optics. The adaptive optics is a mirror, whose surface contour can be adjusted, in the folded beam path inside the resonator. The adjustment is undertaken with the aid of electrically drivable piezoelectric ceramics. To control the drive, a small portion of the output radiation is coupled out, guided through a

diaphragm and passed onto a thermal sensor. Depending on the received radiant power, the individual "mirror elements" are then driven via a control circuit so as to produce a mirror deformation which compensates surface deformations of the other optical components. An analogous adaptive adjustment of a mirror surface in a folded beam path in the resonator is described in L. Flath, J. An, J. Brase, C. Varrano, C.B. Dane, S. Fochs, R. Hurd, M. Kartz, R. Sawvel; "Development of Adaptive Resonator Techniques for High-Power Lasers", the publication relating to the conference entitled "Workshop on Adaptive Optics for Industry and Medicine", Durham (GB); page 163-168, 12-16 July 1999.

The deformation of the laser resonator mirror for compensation purposes is described in N. Kugler, A. Vazquez, H. Laabs, H. Weber, "High-Power Solid-State Laser with Birefringence Compensation and Adaptive Resonator Mirror"; publication relating to the conference "Workshop on Adaptive Optics for Industry and Medicine", Durham (GB); page 149-154; 12-16 July 1999.

Instead of varying the surface curvatures of optical components, in particular of mirrors, under active control, it is also possible for lenses to be displaced along the resonator axis in the laser resonator in order to compensate thermal effects at the active element. Such arrangements are described in St. Jackel, I. Moshe, R. Lavi; "High Performance Oscillators Employing Adaptive Optics Comprised of Discrete Elements"; SPIE Conf. On Laser Resonator II, San Jose, Calif., page 42-49; 12-16 July 1999.

It is likewise possible to have a combination of a plurality of elements in a laser resonator which can be controlled as to their optical action. Thus, in I. Moshe, S. Jackel; "Enhanced Correction of Thermo-Optical Aberrations in Laser Oscillators", SPIE Conf.

on Laser Resonator II, San Jose, Calif., page 181-186; 12-16 July 1999 use is made of a lens which can be adjusted under control as to its distance from the laser resonator mirror and which has one Faraday rotator each upstream and downstream of the active medium.

DE-A 197 14 175 discloses a compensation of the thermal lens in the laser medium which is effective over the entire range of pumping power. The compensation of the thermal lens was achieved by virtue of the fact that a portion of the pumping light itself was used in the case of a longitudinally pumped active medium with its varying power in order to create an appropriate optical element which compensates the thermal lens in the active medium. This element was either a modified launch mirror or an additionally inserted element acting as a lens with a negative focal length (a positive one in the case of a negative thermal lens in the laser medium). It would also be possible to use a gaseous or liquid medium, located in a suitable cuvette, as the element. In addition to the pumping optical radiation, it would also be possible to send a portion of the generated laser power through an appropriate element of the resonator for compensation purposes.

The arrangement described in US-A 3 434 779 served the purpose of keeping a laser power constant, this being achieved by using thermal optical effects.

Constancy is kept by using a nitrobenzene cell which widens a laser beam irradiated into it, doing so as a function of the radiant power. This widened beam then strikes a diaphragm which passes only the central beam region.

The compensation of thermal lensing effects in the laser resonator is described in the publication by

R. Koch entitled "Self-adaptive optical elements for compensation of thermal lensing effects in diode end-pumped solid state lasers - proposal and preliminary experiments"; Optics Communications 140 (15 July 1997), pages 158-164. The compensation was performed by means of a resonator mirror whose mirror substrate absorbed the pumping radiation and had a large positive coefficient of thermal expansion. Specified as a further compensation option was an antireflection-coated plate which had a large negative thermal coefficient of the refractive index.

Further examples are described in US-A 5 386 427, US-A 5 751 750, US-A 3 662 281, US-A 3 609 584, US-A 3 577 098 and US-A 4 848 881.

Object of the invention

The object of the invention is to achieve, by contrast with the prior art, a substantially more effective compensation of the above-described optical changes caused by radial temperature gradients in optical components.

Achievement of the object

The above-named object is achieved by virtue of the fact that by contrast with the prior art, the various functions of absorption (heating by means of radiation absorption), radial thermal conduction (for generating a power-dependent temperature distribution) and thermal dispersion (for generating a thermal lens) are distributed over various, that is to say a plurality of elements with different material properties. By contrast with the prior art, there is now no need for one and the same element to fulfill all functions.

By contrast with the prior art, the aim here is direct heat transfer by means of intimate contact between an

optical component and the compensation medium. The aim is preferably to achieve an approximately identical radial thermal distribution in the optical component and in the compensation medium.

Use may be made as compensation medium of materials which cannot transmit mechanical shear forces, or can transmit only negatively small ones. Such materials are liquids, gels and gases. However, it is also possible to use elastic media (solid bodies). However, in the case of solid bodies it is to be ensured that surfaces bearing against one another do so closely in optical terms, preferably being optically contacted. Optical surface effects should not arise in this case.

This type of compensation can be applied in the case of many optical components; however, they will preferably be used with lasers, in particular high-performance lasers, in which a good beam quality is desired.

Introduced into the beam path of an optical arrangement, which can be a laser oscillator or laser amplifier, for example, is an optical unit for compensating thermal optical effects in the beam path by means of optical components present therein. The optical unit located in the beam path has optical elements which have at least two different material properties and cooperate actively for the compensation, and on which, for the purposes of compensation, heating by means of radiation absorption, thermal conduction for generating a power-dependent temperature distribution, and thermal dispersion for generating a thermal lens can be distributed, preferably with a different effect.

One of the elements has an optical compensation space which is filled, in particular completely filled, with an optically transparent compensation medium. Optically transparent solid bodies are arranged as a further

element with radiation absorption on both sides of the compensation space. The compensation medium makes such close thermal contact with the solid bodies arranged on both sides that good heat transfer is ensured from the solid bodies to the compensation medium. The optical compensation space can now only be the compensation medium when a solid body or a solid gel is involved; however, it can also be a space which is to be filled with the compensation medium if a liquid or a flowable gel is involved.

The compensation space is preferably designed in such a way that it extends perpendicular to the optical axis of the beam path. If the optical unit is used in a laser resonator, the components of the oscillator or amplifier are generally of circular cylindrical design, and cooling takes place at the periphery. Consequently, the compensation space is also designed with radial symmetry relative to the axis of the beam path, and the radial extent of the compensation space relative to the optical axis of the beam path is adapted to that of the neighboring solid bodies. It is preferred to select the radial dimensions of the compensation space and/or of the compensation medium to be identical to those of the adjacent neighboring solid body.

The solid body immediately neighboring the compensation medium will preferably be kept in a cooling holder which preferably completely encompasses the entire envelope of the solid body in intimate thermal contact. This produces a space-saving design with good efficiency.

If a material which transmits no mechanical shear forces is used as compensation medium, it is preferably possible to provide an expansion space which is connected to the compensation space and into which the compensation medium can undertake volumetric equalization in the event of thermal loading. Such an

expansion space will be used chiefly in the case of a liquid or flowable compensation medium. Given a compensation medium of small volume, even only a small gas bubble is sometimes sufficient. If solid, non-flowing compensation media are used, it is possible to dispense with an expansion space, since the thermal expansion is small. The small expansion still present then pushes tightly against the neighboring optical components.

As already indicated above, an optical arrangement with such an optical unit is preferably designed as a laser resonator or laser amplifier in order, for example, to generate high laser output powers with good beam quality. In this case, the active medium is subdivided into partial media. A compensation space filled with a compensation medium is arranged as an optical element between the partial media and as a further optical element of the optical unit, each partial medium acting as an optically transparent solid body of the unit. Here, as well, solid and flowable media can be used as compensation medium. A compensation space into which flowable media can be filled will then be provided for such media. For non-flowable media, the medium itself will be produced with the required spatial dimensions.

The advantages of the invention and its fields of application emerge from the following description.

Brief description of the drawings

Examples of the method according to the invention and of the subject matter according to the invention are explained below with the aid of the figures, in which:

figure 1 shows a diagrammatic illustration of a laser resonator as an optical arrangement with a compensating optical unit,

figure 2 shows a variant of the illustration in **figure 1**, an active laser medium being split here into component elements, and the optical compensation being undertaken immediately between these elements,

figure 3 shows a variant of the exemplary embodiments illustrated in **figures 1 and 2**, and

figure 4 shows a variant of the optical arrangement illustrated in **figure 3**, there being a plurality of optical compensation elements, however.

Ways of implementing the invention

The laser resonator **1**, illustrated by way of example in **figure 1**, is designed as a symmetrical resonator with two parallel mirrors **3a** and **3b**. Arranged in the laser resonator **1** are a laser rod **5** as active medium, two lenses **7a** and **7b** and the optical unit **9** according to the invention. As indicated diagrammatically by the arrows **11a** and **11b**, the laser rod **5** is pumped optically in a transverse fashion. This pumping heats the laser rod **5** in its interior. It is cooled on its exterior. The result is the formation of a temperature gradient in the laser rod **5**; what is termed a thermal lens has been formed. The refractive power of this thermal lens changes with the irradiated pumping energy and the generated laser radiation, which leads in turn to variations in the mode of oscillation of the laser resonator, and then further influences the generated radiant power and modes thereof. Such a behavior is extremely undesirable.

In the laser resonator **1** sketched in **figure 1**, the two lenses **7a** and **7b** are used for the purpose of optimum superimposition of the thermal lens in the laser rod **5** with that in the unit **9**.

The unit **9** used for thermal compensation comprises here two laterally cooled, optically transparent cylindrical rods **13a** and **13b** and a narrow compensation space **15** with a compensation medium **16**. The compensation space **15** extends at right angles to the optical axis **14** of the beam path produced by the laser rod **5**. A liquid or a gel can be used as compensation medium. Use may be made as compensation materials of water, deuterated water or optical liquids and gels such as, for example, preferably for the visible spectral region OCF-446, OCF-452, OCF-463, OC-431 A-LVP, OC-440, OC-459, OC-462, OCK-433, OCK-451. These products are produced, for example, by the company Nye Optical Products. A further compensation material is a silicone "SYLGARD 182" from Dow Corning. Use will preferably be made of fully deuterated, chlorinated and fluorinated gels or liquids for the spectral region of longer wavelength adjoining the visible region. Of course, other liquids and gels can be used. It is also possible to use gases with suitable optical and thermal properties (refractive index, thermal dispersion). The advantages of liquids and gels are a very pronounced negative thermal dispersion (dn/dT) and the absence of thermally induced birefringence, since pressure gradients caused by thermal expansion cannot arise. These compensation media do not transmit any mechanical shear forces. An expansion space **19** is provided for volumetric equalization when the compensation medium is thermally loaded.

The rods **13a** and **13b** as well as the compensation medium 16 are cooled externally by a holder **17**. Glass or, even better, a birefringent crystal comes into consideration as rod material for avoiding thermally induced depolarization. A birefringent crystal as rod **13a** or **13b** is particularly advantageous whenever the laser rod **5** is likewise birefringent. The crystal optic axes are to be aligned with one another.

The medium **16** is now heated to a small extent by absorption of a small portion of the transmitting laser radiation (residual absorption), and to the other extent by thermal conduction from the neighboring rods **13a** and **13b** into the medium **16**. For their part, the rods are heated by absorption of a small portion of the laser radiation transradiating them. It would also be possible, in addition, to irradiate heat transversely from a heat source. In order to produce a power-dependent lens suitable for compensation in the compensation medium **16**, too, power-dependent temperature distribution must be set up therein. This requires that the thermal conduction must take place in a predominantly transverse fashion from the material (transverse to the axis **14** of the beam propagation). Particularly in the case of compensation media which are narrow in the direction of beam propagation, predominant cooling over the end faces would have the effect that a temperature distribution set up is influenced chiefly by the intensity distribution of the transmitted beam and only to a slight extent by the power thereof. This process is avoided in the unit **9** by arranging the compensating medium between rods **13a** and **13b** which are heated by a slight absorption of the transmitted laser beam and are radially cooled. The desired power-dependent temperature distribution is now produced by the processes of heating, cooling and thermal conduction in the rods **13a** and **13b** and in the medium **16**, and transmitted to the compensation medium **16** by thermal contact.

Instead of heating only the rods **13a** and **13b**, the heating can be performed by a low absorption of radiation in the compensation medium **16**. Irrespective of whether the heating is predominantly produced by absorption in the compensation medium **16** or in the rods **13a** and **13b**, the desired power-dependent lens is set up owing to the thermal contact of the compensation medium

16 with the neighboring rods **13a** and **13b**, and to the radial cooling of the rods **13a** and **13b**. By contrast with the prior art, the different functions of absorption (heating), radial thermal conduction (for generating a power-dependent temperature distribution) and thermal dispersion (for generating the thermal lens) are distributed here over various elements with different material properties, and need not all be fulfilled by one and the same element.

The strength of the lens produced and, if appropriate, the absorption can be optimized by mixing various materials (for example water and heavy water), and by selecting a suitable thickness **d** of the compensation space **15**. By cooling the periphery of the rods **13a** and **13b** with the aid of a holder **17** which encompasses them and which likewise cools the compensation medium **16** externally, a power-dependent, radially decreasing temperature distribution is produced, which leads to a power-dependent lens because of the thermal dispersion of the compensation medium **16**. The temperature distribution in the compensation medium **16** is approximately equal to that in the neighboring rods **13a** and **13b** because of the small dimension of the thickness of the compensation space **15**.

The compensation medium **16** and the rods **13a** and **13b** preferably have the same refractive index. As a result of this, no Fresnel reflections occur at the interfaces between the rod end face and compensation medium **16**, and a deformation based on the thermal expansion of the rods **13a** and **13b** does not lead to a lensing effect. The Fresnel reflections could certainly be suppressed by an antireflection coating, but this would entail making the unit **9** more expensive. The liquids and gels listed above are particularly suitable, because their refractive index can be set.

The compensation space **15** can have two plane-parallel boundary surfaces (end faces of the rods **13a** and **13b**). However, it is also possible to undertake specific shaping such that even the higher aberrations, occurring in the laser rod **5**, of the thermal lens can be adaptively compensated.

Given a sufficiently high thermal dispersion of the compensation medium **16**, the thickness **d** of the compensation space **15** can be selected to be so small that no convection occurs. Specifically, convection would lead to striations. The convection can be avoided by selecting the viscosity suitably, and this is possible with the abovementioned materials by using suitable additives.

Data on the arrangement of the individual components are illustrated in **figure 1**. Here, the laser rod **5** is an Nd:YAG with a refractive index of $n_L = 1.82$, a length of $L_L = 50$ mm and a diameter of 4 mm. One end face of the laser rod **5** has an axial distance of $\mathbf{Z} - L_L/2n_L$ from one resonator mirror **3a**. **Z** is the distance between a resonator mirror **3a** or **3b** and the principal plane of the thermal lens. The magnitude of **Z** influences the mode magnitude and the stability range of the laser resonator **1**. $\mathbf{Z} = 80$ mm. The focal length **F** of each lens **7a** and **7b** is 100 mm. The optical unit **9** has an axial length $\mathbf{L_K}$ of 20 mm. The rods **13a** and **13b** are made from glass with a refractive index of $n_K = 1.5$ and a diameter of 4 mm. The thickness **d** of the compensation space **15** is smaller than 1 mm. OCF-446 has been used here as compensation medium **15**.

If the thickness **d** is selected to be substantially larger, the viscosity of the compensation medium must also be increased, or a solid body must be used in order for there to be no convection accompanied by striations.

A long path **Z** produces a larger mode diameter of the generated laser radiation, and thus a better beam quality, and this can be achieved by a lens placed additionally in the resonator. The distances **Z** between the resonator mirror **3a** or **3b** and the principal plane of the thermal lens need not be selected to be equal on the left and right in the resonator **1**. Then, the two resonator mirrors **3a** and **3b** need not be of planar design; they can also be arcuate. All that is involved here is one of many design variants, all of the optical components being variable.

The rods **13a** and **13b** can, of course, also have a cross section which is square, cuboid or of regular or irregular polygonal design. Again, the cross sectional contour can vary over the rod length. The rod length can be greater than the transverse rod dimension, but also substantially smaller than this (for example thin disks).

Instead of a solid rod **5** as active medium, it is also possible to use another amplifier medium (discharge tube [gas laser], liquid [dye laser], ...). The compensation of optical thermal effects is also not limited to laser resonators; it can also be used in the case of mechanisms based on nonlinear optical processes (frequency doubling, parametric amplification and oscillation, ...).

A further design variant of a laser resonator **29** is illustrated in **figure 2**, a laser rod having been subdivided here into a plurality of small partial rods **30a** to **30d**, between which compensation is then undertaken. By analogy with **figure 1**, a compensating optical unit **34a** to **34c** now comprises in each case the two neighboring optically transparent solid bodies, that is to say the partial rods **30a** and **30b**, **30b** and **30c**, and **30c** and **30d**. The compensation medium **39** is then arranged between the end faces of the neighboring

partial rods. The partial rods **30a** to **30d** are provided externally with a cooler **31**, which simultaneously cools the compensation medium **39** in the compensation units **34a** to **34c** with the aid of the holders **35** thereof. The resonator mirrors are marked here with **37a** and **37b**.

Owing to the heating in the laser rods and to the lateral cooling, a power-dependent temperature distribution, and thus a power-dependent positive thermal lens are set up in the partial rods **30a** to **30d**. Owing to the thermal contact between the end faces of the thermal rods **30a** to **30d**, this temperature distribution in the partial rods **30a** to **30d** is transmitted to the compensation medium, marked here with **39**. As a result, a negative thermal lens, which compensates the positive thermal lens of the partial rods **30a** to **30c**, is produced in the compensation spaces **41a** to **41c** by the compensation medium **39** located there. There is no need in the compensation medium either for absorption of the laser power or of the pumping radiation. However, it is also possible to incorporate controlled absorption of the pumping light or of the laser radiation in the compensating medium. To be specific, all media absorb as a rule.

Intrinsically birefringent material, such as Nd:YVO_4, for example, is preferably used for the laser rods. In that case, disturbing thermally induced birefringence does not occur either in the partial rods **30a** to **30c** or in the compensation medium. The optical axis of the partial rods **30a** to **30c** is aligned at right angles to the resonator axis **43**. In order to average out any possible asymmetry in the thermal lens caused by the anisotropy of the material of the partial rods **30a** to **30c**, the partial rods are arranged such that the optical axes are twisted in each case by 90° relative to one another in neighboring partial rods. In addition, the polarization of the transmitted laser radiation can then likewise be rotated by 90° between

the individual partial rods **30a** to **30c** by suitable optical elements. The amplification of the laser radiation can be optimized in this way (anisotropy of the crystals). In addition, it would also be possible as an alternative to design the end faces of the partial rods in an arcuate fashion. Quartz rotators must be used if no birefringence occurs.

It will be preferred here to design the thickness of the compensation spaces **41a** to **41c** to be under 1 mm (for example 0.5 mm to 1 mm). The length of the partial rods can be a few millimeters to a few centimeters in the case of a typical rod diameter of 4 mm. **Z** will typically be selected between 20 mm and 100 mm.

What has been set forth above with reference to the heat transfer and the geometry for the rods **13a** and **13b** is also valid mutatis mutandis for the partial rods **30a** to **30d**.

Transverse pumping of the laser rod **5** or **30a** to **30d** is illustrated in **figures 1** and **2**. Of course, it is also possible to use longitudinal pumping or other exciting mechanisms (gas discharge, RF excitation, gas dynamic, electronic, electric excitation, electron gun, ..) of the laser medium.

A variant of the optical arrangements shown in **figures 1** and **2** is illustrated in **figures 3** and **4**. The variants illustrated here are simpler in their mechanical design. They can be used both for flowable and for non-flowable compensation materials. An exemplary use of the non-flowable compensation materials is described below.

A laser resonator **47** similar to that in **figure 2** is shown in **figure 3**. However, the laser resonator **47** exhibits substantial differences by comparison with the laser resonator **29**. Here, a solid body, preferably an

elastomeric material, specifically the two-component gel OCK-433 mentioned above is used, in the cured state, as a unit **49** compensating thermal effects.

A double laser rod **50a/50b** is arranged as active medium in the laser resonator **47**, the two rods **50a** and **50b** being separated from one another by the compensating unit **49**. The compensating unit **49** has a compensating medium **51**, here the cured OCK-433, which is surrounded by a transparent sleeve **53** in which one end region **54a** or **54b** of the two end regions of the two rods **50a** and **50b** is plugged in each case. The cured OCK-433 serves firstly as compensation medium, and secondly also as a (cured) adhesive which lends the overall arrangement a stable coherence. The sleeve **53** is fabricated from sapphire, for example. Sapphire is transparent and has a very good thermal conductivity. Since the laser rods **50a** and **50b** generally have a circular cross section, the sleeve **53** is also designed with a circular cross section. The end regions **55a** and **55b**, not plugged in the sleeve **53**, of the laser rods **50a** and **50b** are held in a holder **57** in a similar way as the arrangement in **figure 2**. The two laser rods **50a** and **50b** as well as the sleeve **53** are situated inside a transparent tube **60**, which is filled with a cooling liquid **59** and which is likewise held in the holder. The two laser rods **50a** and **50b** as well as the sleeve **53** are cooled at their envelope by the cooling liquid **59**. As is indicated by the two arrows **P**, the two rods **50a** and **50b** are pumped transversely in optical terms. The two resonator mirrors **62a** and **62b** are arranged at right angles to the optical resonator axis **61** in a fashion distanced from the outer end faces **63a** and **63b**, respectively, of the rods.

A very good thermal contact between the rod end faces and the compensating medium **51** is important. If, for example, the two-component gel OCK-433 is used, this can be introduced while still liquid between the rod

end faces. The gel is subsequently cured, forming a good thermal contact.

If use is made of elastomeric compensation media, they can be pressed over the adjacent laser rods **50a** and **50b** by means of the holder.

If, instead of an elastomeric material, use were made of a material with a higher modulus of elasticity, it would be necessary for the end faces and the assigned surfaces of the medium to be produced in a fashion adapted to one another in such a way that no "air transition" remains; optical contact would have to be made between the two neighboring surfaces. As regards heating (absorption), radial thermal conduction (for producing a power-dependant temperature distribution) and thermal dispersion (for producing a thermal lens), the same applies for this arrangement as for the arrangement previously described.

Figure 4 shows a further design variant, which is constructed in a way similar to that illustrated in **figure 3**. However, here the active medium is split into four rods **67a** to **67d** aligned with one another. The optical axis of the laser rods **67a** to **67d** coincides with the optical axis **69** of the laser resonator **70**. The two middle rods **67b** and **67c** are designed with the same length; likewise the two outer ones **67a** and **67d.** Each of the outer rods **67a** and **67d** is only half as long as each of the two middle rods **67b** and **67c.** Also present are three compensating units **71a, 71b** and **71d** for compensating thermal optical effects which comprise a compensating medium **72** and a sleeve **73.** The arrangement relating to the laser rod end faces is undertaken in a way similar to the design in **figure 3**. Here, as well, the laser rods **67a** to **67d** and the sleeves **73** of the units **71a** to **71c** are cooled in a way similar to **figure 3** by a liquid **76** flowing in a transparent tube **75.** The holder **77** for the tube **75** and the laser rod

arrangement - **67a** to **67d** with **71a** to **71c** - corresponds to the holder **57** shown in **Figure 3**.

If high laser output powers are to be generated, long laser rods are also generally selected. If split up into a plurality of laser rods by comparison with the arrangement in **figure 3** this produces a better thermal optical compensation. What held for the laser rods **30a** to **30c** holds for the laser rods **50a** and **50b** and **67a** to **67b.**

As a rule, as a consequence of thermal optical conditions, a laser rod generates a thermally induced birefringence in the case of which a lower refractive index is produced for the radially polarized radiation component than for the tangentially polarized one. The compensating solid medium is now selected in the above exemplary embodiments in such way that the reverse effect is produced in the event of heating.

As already mentioned at the beginning, instead of the solid two-component gel OCK-433 it is also possible to use a liquid as compensation medium in the optical arrangement illustrated in **figures 3** and **4**. A small gas bubble which does not disturb the beam path will then preferably be provided for the purpose of volumetric equalization. However, it is also possible to dispense with the volumetric equalization.

If solids, that is to say non-flowable materials are used as compensation media, it is possible to dispense with the sleeve **53** or **73** if the compensation medium behaves inertly relative to the cooling liquid.